A Data GAP Analysis and Inland Inundation Survey for the Delaware Coastline:

Final Report and Recommendations

Submitted to

Delaware Department of Natural Resources and Environmental Control

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Project Summary

In the last two decades storms such as Hurricanes Katrina and Ike along the Gulf of Mexico and Floyd and Hugo along the Atlantic Coast of the United States have resulted in significant loss of life, injuries and property damages reaching well over 100 billion dollars. Much of the damage during these and other tropical and extra-tropical weather systems is associated with severe coastal flooding. The Delaware coastline is extremely vulnerable to such events, examples being the great March, 1962 storm and the recent coastal flooding incident of May 12, 2008. A GAP Analysis of pertinent coastal data needs and a comprehensive survey of inland inundation levels during previous coastal flooding events have been completed as part of a cooperative effort between the University of Delaware and several Delaware State Agencies. The goal is to better monitor conditions along the Delaware coastline and to provide advance warning of impending coastal flooding events.

This project included an exhaustive inventory of real-time and archived data suitable for coastal flood monitoring and research. The inventory includes meteorological, tidal, stream flow and buoy data sources, along with ancillary sources of coastal information (i.e. research publications, non-digital records, modeling, etc.). The inventory has lead to a series of recommendations as to the data needed to reach an "optimum" coastal monitoring network, and the spatial placement and temporal resolution of additional sensors that may need to be deployed to reach the optimum configuration. Thus, the GAP Analysis defines the present state of coastal data collection efforts across the state, suggests an "optimum" data collection network for coastal flood monitoring and research, identifies "gaps" in the present network of stations and recommends data that need to be added to the current network configuration. An inventory of available high water marks from previous coastal flooding events has been created to aid in understanding the relationships between water levels at tidal monitoring points and inland locations. All available high water records have been identified, their history confirmed and the inundation level recorded. Much of this data has been transcribed from handwritten forms to digital media. The verification of the handwritten material will continue beyond the duration of this project. The inundation data will be used in conjunction with observed tide heights at tidal monitoring points to better understand the inland inundation associated with various tidal levels along the coast.

1.0 Problem Statement:

Previous meteorological events have shown the Delaware coastline to be highly vulnerable to coastal flooding. Although several sources of meteorological and tidal data are available in real-time, a comprehensive survey of coastal data availability has not been conducted for the State in order to identify important data gaps. In addition, little data currently exists linking observed tide heights at coastal monitoring sites to inland inundation levels. Both of these issues must be addressed before a comprehensive coastal monitoring system can be developed for Delaware. This project represents the initial year in a multi-year project that seeks to develop a real-time coastal flood monitoring system for the State of Delaware and to develop the capacity to monitor the effects of potential sea-level rise.

2.0 Results of Coastal Storm Data Inventory

The Delaware coastal data GAP Analysis is designed to define the current state of coastal data collection efforts throughout the Delmarva region through an exhaustive inventory of real-time and archived data sources. Sources inventoried include meteorological, tidal, buoy, stream flow and inundation data sources, along with other types of ancillary data which pertain to coastal flooding issues (i.e. research publications, modeling studies, photographic evidence, etc.). Based upon the data inventory, a recommendation for an "optimum" data collection network for coastal monitoring has been developed, including proposals for new data sources to fill gaps in the present network of observing sites. The GAP Analysis data inventory has identified the following data sources for use in operational coastal monitoring and for research into coastal flooding issues. The region inventoried represents those portions of the Delmarva Peninsula, southeast Pennsylvania and southern New Jersey whose data may have a bearing on coastal flood issues along the Delaware coastline (Figure 2.1). These data and additional ancillary data sources will also be made available on the project web site (http://www.deos.udel.edu/delawaregap).

2.1 Meteorological Data Sources

The survey of meteorological data useful for coastal monitoring and research identified 125 stations across the Delmarva region that currently collect meteorological data (Appendix 1; Figure 2.2). More than one-half (75) of these stations report meteorological data in near real-time and are available from the Delaware Environmental Observing System (Figure 2.3; DEOS; www.deos.udel.edu), while most of the remainder are National Weather Service (NWS) Cooperative Observer (COOP) stations that report daily data (maximum temperature, minimum temperature, liquid precipitation, snowfall and snow cover) that is generally not easily accessible for days or weeks after the observation is taken. These data can be found on the web site of the National Climatic Data Center (NCDC; http://www.ncdc.noaa.gov/oa/ncdc.html). The spatial distribution of current meteorological stations (both real-time and near real-time) is relatively homogeneous across the region, with the exception of gaps along coastal areas (see Section 4 for recommendations).

Another 123 stations were identified that at one time collected meteorological data but are no longer active (Appendix 2; Figure 2.4). The data from legacy stations, although not important for operational work, are of great importance in research into coastal flooding issues. Of these stations, 111 are former NWS COOP stations that have daily data available for research purposes (http://www.ncdc.noaa.gov/oa/ncdc.html).

2.2 Tidal Data Sources

Twenty-eight tidal stations, that currently record data, were identified in the survey (Appendix 3; Figure 2.5). Data from all of these stations are available real-time through the United States Geological Survey (USGS) web page (http://waterdata.usgs.gov/de/nwis/sw), the National Ocean Service (NOS) web page (http://www.ndbc.noaa.gov/rmd.shtml) or through DEOS. Data exist for some of these stations for more than 50 years; however, most have a significantly shorter period of record. Figure 2.5 indicates that there are large areas of the Delaware coastline where tidal water levels are not currently being monitored, especially along Delaware Bay.

Thirty-six legacy tidal stations were identified in the inventory (Appendix 4; Figure 2.6). Although these stations are no longer active, many have relatively long periods of record that can be used to better understand the relationship between coastal water levels and inland tidal inundations. Historical data from these stations is available on the USGS and NOS web sites. As with the active tidal stations, few legacy stations exist along the Delaware Bay coastline.

2.3 Stream Flow Data Sources

Stream flow is an important component of coastal flooding as many storms include heavy coastal and inland precipitation that results in large stream discharge at the coast which exacerbates coastal flooding concerns. The inventory identified 42 stations that observe stream flow across the Delmarva region (Appendix 5; Figure 2.7). The data from all of these stations is available online, real-time on the USGS (http://waterdata.usgs.gov/de/nwis/sw) and DEOS (www.deos.udel.edu) web sites. Inspection of Figure 2.7 indicates a dearth of stations in both Kent and Sussex Counties. The majority of stations are located in the piedmont or near piedmont region of New Castle County, DE and Chester County, PA.

Nearly 500 legacy stream flow stations exist across the region (Appendix 6; Figure 2.8). Many of these stations have long periods of record and should prove very useful in understanding the relationship between stream flooding and coastal flooding events. In addition, legacy stations are more numerous across southern Delaware (compared with current stations) which should allow researchers to develop a more complete picture of the influence of stream flow on coastal flooding in Kent and Sussex counties.

2.4 Buoy Data Sources

Currently, 6 buoys are placed in near shore waters in the environs of the Delaware Coast and Delaware Bay (Appendix 7; Figure 2.9). In general, these buoys observe meteorological conditions and/or wave characteristics. Two of the buoys are operated by NOAA's National Ocean Service, two by the United States Army Corps of Engineers (http://sandbar.wes.army.mil/) while the others are operated by the Delaware Coastal Management Program (DCMP). The data from these buoys are available real-time on the DEOS web site (www.deos.udel.edu).

In total, 151 environmental monitoring platforms currently observe the Delmarva Region and report data in real-time (Figure 2.10). These observations include 75 meteorological monitoring stations, 42 stream gauging stations, 28 tidal monitoring stations and 6 ocean buoys. Unfortunately, the spatial placement of the stations and their temporal reporting characteristics do not provide an optimum coastal flood monitoring network for Delaware. Section 4.0 will discuss the additional data sources needed for an optimal coastal monitoring system.

3.0 Storm Inundation Data Survey

An important component of a comprehensive coastal flood monitoring system for Delaware is the ability to relate previous inland inundation levels to tidal monitoring sites along the coast. High water marks have been identified, their history confirmed and the inundation level recorded for each site. The association between tide levels at active coastal monitoring sites and inland flood levels is critical in developing statistical relationships that can be used in the development of coastal flood models that accurately depict possible inland flooding given a forecast of tidal anomalies at active monitoring sites.

3.1 Handwritten Records Retrieval

Much of the useful data on high water marks associated with various storms is available only in "hardcopy" (non-digital) form. Several of the documents pertaining to inundation levels were located from conversations with various Delaware State agencies. These documents have been scanned, and their data digitized. In addition, photographs of coastal flooding events have been obtained that may be used to estimate high water marks. These documents will be made available on the project web page (http://www.deos.udel.edu/delawaregap) as the material is too voluminous for this report. However, Appendix 8 gives surveyed and measured high water marks for several of Delaware's major coastal flooding events of the last five decades. These high water marks cover a substantial portion of the Delaware coastline, but are still relatively few in number. A map showing the geographic location of several of the high water marks is included within Appendix 8. All high water marks with available latitude and longitude coordinates were converted to a standard datum (NAVD88) in the Appendix. Additional non-digital records exist for coastal areas concentrated mainly in the Inland Bays area of the state (Figure 3.1). These data have been scanned and digitized and are available on the project web page.

An example of the non-digital records is given in Figure 3.2. Over 700 additional coastal water level measurements have been identified and may be used in future research projects. However, measurement techniques for these sites are non-homogeneous both spatially and temporally across locations. Diverse techniques were utilized to obtain the high water marks reported at different stations. Moreover, dissimilar measurement techniques were used at the same station from one time to another (i.e. is the water level measured from the bottom of the insert, the top of the insert). To obtain a truly useful data set for coastal flood research, the data must be standardized to a common datum by careful analysis of the comments on the handwritten records.

4.0 Recommendations

The following is a list of recommendations for enhancing coastal flood monitoring efforts across the Delmarva Region. This list was developed after consideration of the current spatial and temporal distribution of measurements and the data needs for a truly comprehensive coastal flood monitoring network.

1) ***Retrofit USGS tide gages with cell modem technology to enhance real-time data availability*** - Although most USGS tidal monitoring sites make observations of water level at a frequency of six minutes, the data is generally available to decision makers with a lag time of at least 30 minutes (generally longer). We recommend retrofitting the following USGS tidal monitoring sites with cell modem technology to allow data polling at six minute intervals and immediate publication to the web. These sites were chosen for communication upgrades based upon their critical placement in flood prone and populated areas of Delaware. More information on the reason for communication upgrades is given with each station below.

   Murderkill River at Bowers Beach, DE – This is the only station along the central section of the Delaware Bay coast. This is also a highly flood prone area that has seen significant damage from coastal storms in the past.

   Indian River at Rosedale Beach, DE – This is the only station located in the "Back Bays" where increased population and development has caused significant flooding issues.

   Nanticoke River at Sharpstown, MD – This station represents the only tidal observations associated with flooding from the Chesapeake Bay into Delaware and is critical to monitor flooding in the Seaford area.

   Rehoboth Bay at Dewey Beach, DE – This station is one of three along the Atlantic Coast of Delaware. The proximity of Route 1 to the coast and the relatively high population density (especially during the warm season) makes monitoring of the tide heights extremely important at this location. This is

especially true given the history of flooding during coastal storm events along Route 1, other main roads and evacuation routes.

Indian River Bay Inlet near Bethany Beach, DE – Please see Rehoboth Beach explanation above.

Little Assawoman Bay at Fenwick Island, DE - Please see Rehoboth Beach explanation above.

Christina River at Wilmington, DE – This station is needed for higher temporal resolution monitoring of coastal flooding along the Delaware River along the Wilmington, DE metropolitan area. It is also the station located farthest north in the Delaware River estuary (within the State of Delaware).

2) ***Add tidal monitoring sites, especially along the Delaware Bay Coast of Delaware*** – There are large spatial gaps between tidal monitoring sites, especially along the Kent and New Castle County coastlines. Tidal levels in the Delaware Bay have historically been more localized and dependent upon specific wind fetch over the Bay than tides along the Atlantic coast of Delaware. Thus, more observations along the central Bay coast would lead to a better understanding of the place-specific tidal conditions, and flooding potentials along the western side of the Delaware Bay. Specifically, we recommend the placement of additional tide gages near the following locations. Explanations for these recommendations are given with each location below and they are ranked in order of priority of installation.

Mispillion Light/Slaughter Beach/Prime Hook, DE area – Currently, the only tidal observation platform along the central Delaware Bay coastline of the State is located at the Murderkill River at Bowers Beach. It is approximately 25 miles (straight line) between the NOS tide gage site at Lewes and the Murderkill location. Given the history of localized flooding along the Bay coast, a 25 mile gap is too great. Thus, to adequately monitor the tidal conditions along the western shore of the Delaware Bay a site is needed at this location which is approximately half-way between the two existing sites. **(priority 1)**

Longneck/Pot Nets Cove area (Inland Bays) – Currently, the only tidal station located within the Indian River/Rehoboth Bay system is located along the Indian River at Rosedale Beach. This single site does not capture the complex nature of flooding along the western side of the Inland Bays. Given the rapid development of the area around this bay system, we propose an additional site further north and east in Indian River Bay to adequately monitor "Back Bay" flooding. **(priority 2)**

New Castle, DE area – Although there are two tidal observing sites located in the Wilmington area, both are located along the Christina River, upstream of the Delaware River. Given the high population density of the Wilmington area and the well documented flooding concerns in this vicinity, a tidal monitoring site is recommended in this area. In particular, recent coastal flooding in the New Castle area merits better monitoring along this flood prone section of the Delaware Bay/River. **(priority 3)**

Woodland Beach/Collins Beach, DE area – This area is approximately 11 miles to the north of the proposed Port Mahon site (see priority 5) and 15 miles south of the NOS station at Reedy Point, DE. A 10 to 15 mile distance between tidal monitoring sites along the complex western Delaware Bay coastline would seem an adequate monitoring interval given the historical record of localized coastal flooding along this coast. **(priority 4)**

Port Mahon, DE area - It is approximately 35 miles (straight line) between the USGS tide gage at the Murderkill location and the NOS tide gage at Reedy Point, DE. Given the history of localized flooding along the Bay coast, a 35 mile gap is unacceptable for sufficient monitoring. Thus, to adequately monitor the tidal conditions a site is needed in the Port Mahon area which is approximately 10 miles north of the Murderkill site. **(priority 5)**

3) ***Develop a comprehensive web site for data associated with coastal flooding*** – Although much of the data associated with coastal flooding exist, there is currently no centralized location to obtain either real-time or archived data to aid in coastal monitoring, modeling, mitigation or other research studies. The results of this GAP analysis will be published to a project web site with the associated maps, data spreadsheets, links to data providers, etc.

4) ***Develop a real-time coastal flood monitoring and warning system for Delaware*** – There is currently no comprehensive coastal flood monitoring or warning system available to decision makers along the Delmarva coastline. We recommend that such a system be established. This process is ongoing with a pilot study for Kent County, DE with funding from NOAA through DNREC Coastal Programs and NSF EPSCOR.

5) ***Install inland inundation water level monitoring sites*** – The relationship between tide levels at the coast and inland inundation is a critical component for development of a coastal flood monitoring system. We recommend installation of a number of sites in flood prone localities to measure water depths during flooding situations. These sites may be constructed in cooperation with the Delaware Department of Transportation who has expressed interest in measuring

inland inundation for transportation management purposes. A comprehensive protocol for these measurements should be developed prior to installation.

6) ***Standardize datums for tidal and stream flow measurements*** - Tidal and stream flow data are currently measured using diverse vertical datums (see Appendices 3 – 6) that make direct comparison of flood levels difficult from station-to-station and from event-to-event. We strongly recommend that the State adopt a single, standard datum for use in coastal monitoring and research initiatives. We recommend using NAVD88 as the standard datum for coastal flood monitoring.

For each data type, the following "metadata" have been collected as part of the inventory:

Meteorological Data (Appendices 1 and 2)

Station Location Name
COOP ID
WBAN ID
WMO ID
FAA ID
NWS ID
ICAO ID
DEOS ID
Data Source (i.e. NWS, NOS, DEOS, etc.)
Station "Owner" (who maintains the station)
Latitude (tenths of degrees)
Longitude (tenths of degrees)
Elevation (meters)
Variables measured (if available)
Start Date (date data collection began)
End Date (date data collection ended; current if still collecting data)
Measurement Frequency (if available)
Real-Time Availability (is the data currently available in real-time)

Tidal Data (Appendices 3 and 4)

Station ID
Station Name
Data Source (i.e. NWS, NOS, DEOS, etc.)
Station "Owner" (who maintains the station)
Latitude (tenths of degrees)
Longitude (tenths of degrees)
Elevation (meters)
Variables measured (if available)
Start Date (date data collection began)
End Date (date data collection ended; current if still collecting data)

Measurement Frequency (if available)
Real-Time Availability (is the data currently available in real-time)
Datum
Comments on Station

Stream Flow Data (Appendices 5 and 6)

Station ID
Station Name
Data Source (i.e. NWS, NOS, DEOS, etc.)
Station "Owner" (who maintains the station)
Latitude (tenths of degrees)
Longitude (tenths of degrees)
Elevation (meters)
Variables measured (if available)
Start Date (date data collection began)
End Date (date data collection ended; current if still collecting data)
Measurement Frequency (if available)
Real-Time Availability (is the data currently available in real-time)
Datum
Comments on Station

Buoy Data (Appendix 7)

Station ID
Data Source (i.e. NWS, NOS, DEOS, etc.)
Station "Owner" (who maintains the station)
Latitude (tenths of degrees)
Longitude (tenths of degrees)
Elevation (meters)
Variables measured (if available)
Start Date (date data collection began)
End Date (date data collection ended; current if still collecting data)
Measurement Frequency (if available)
Real-Time Availability (is the data currently available in real-time)
Comments on Station

Figures

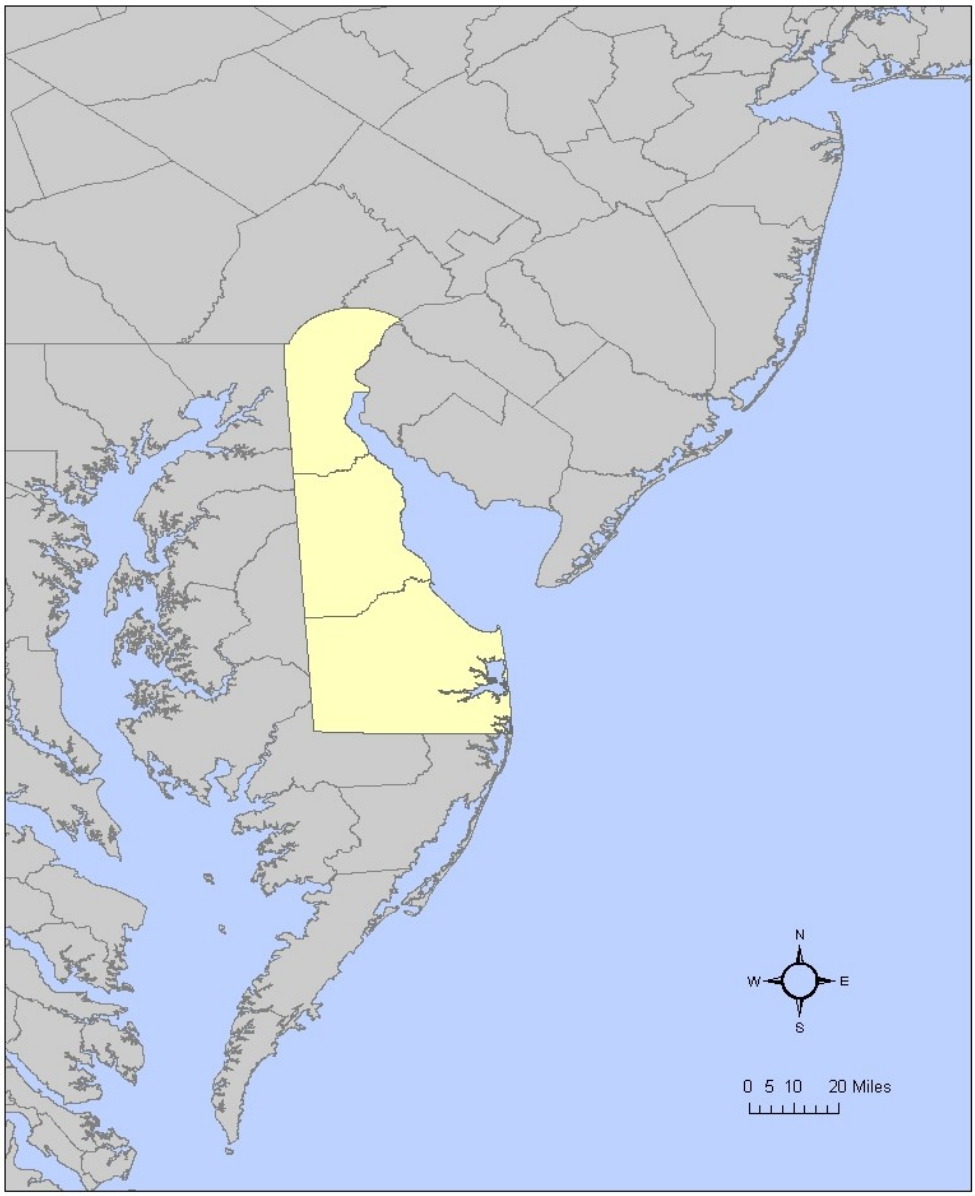

Figure 2.1. General study area used for inventory of coastal flood related data sources.

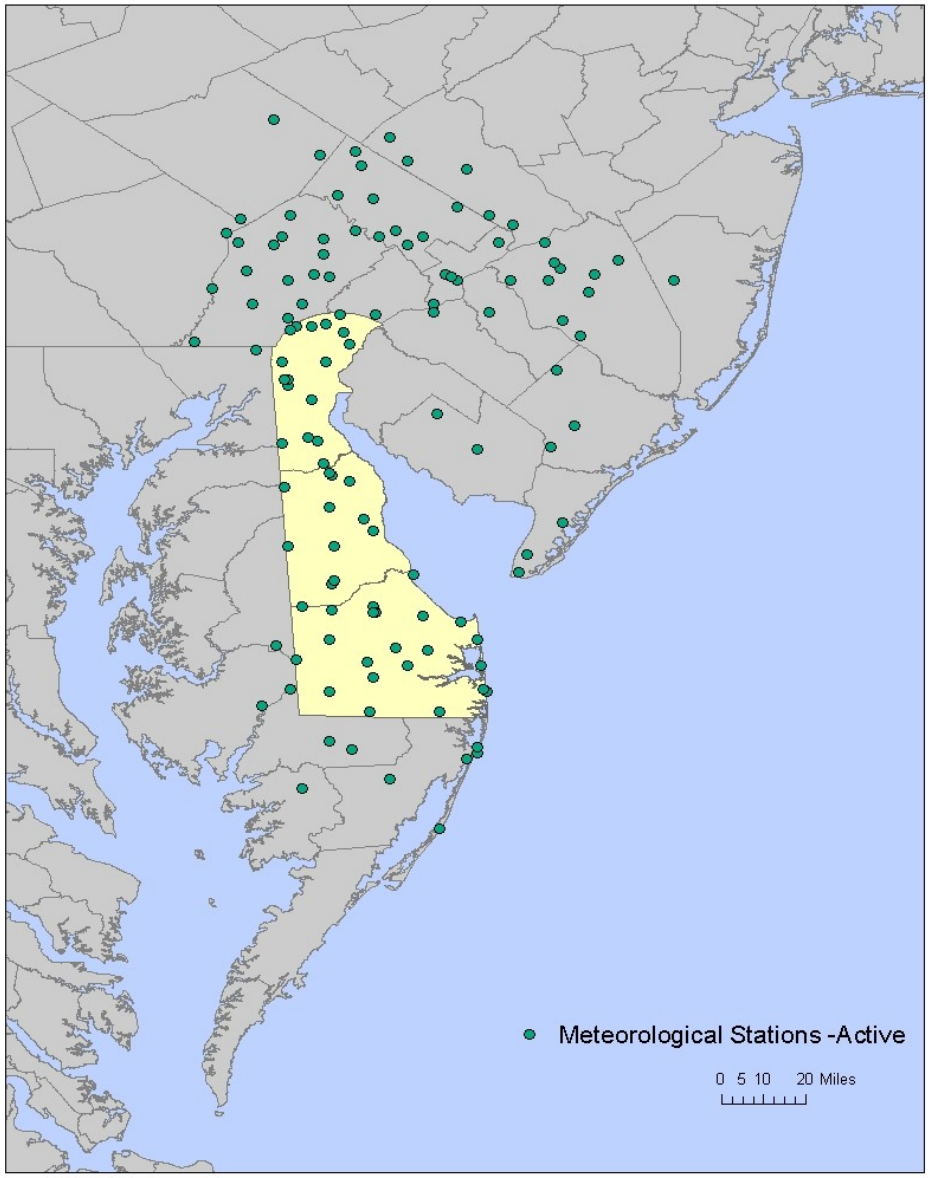

Figure 2.2. Location of stations currently making meteorological measurements in the Delmarva Region.

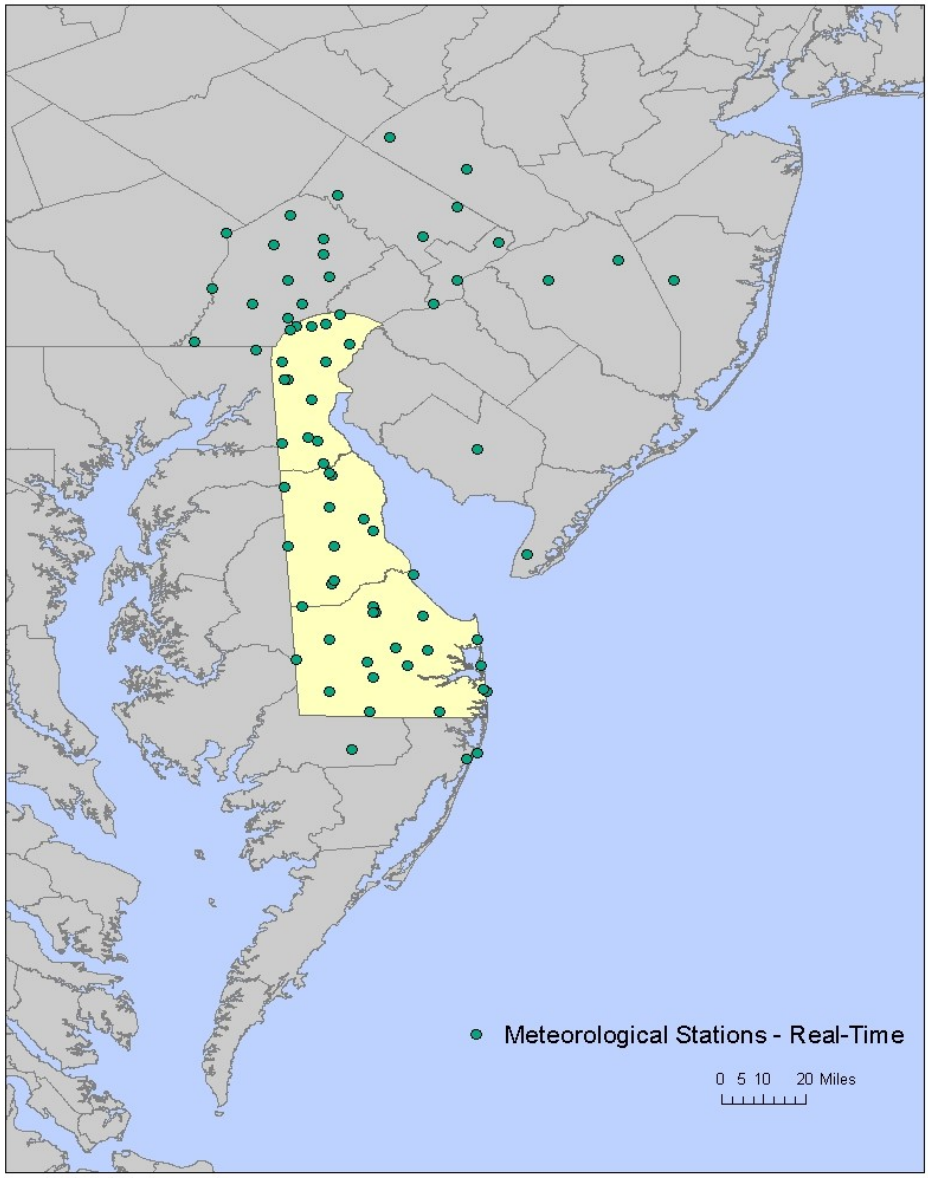

Figure 2.3. Meteorological observing stations across the Delmarva Region available in real-time.

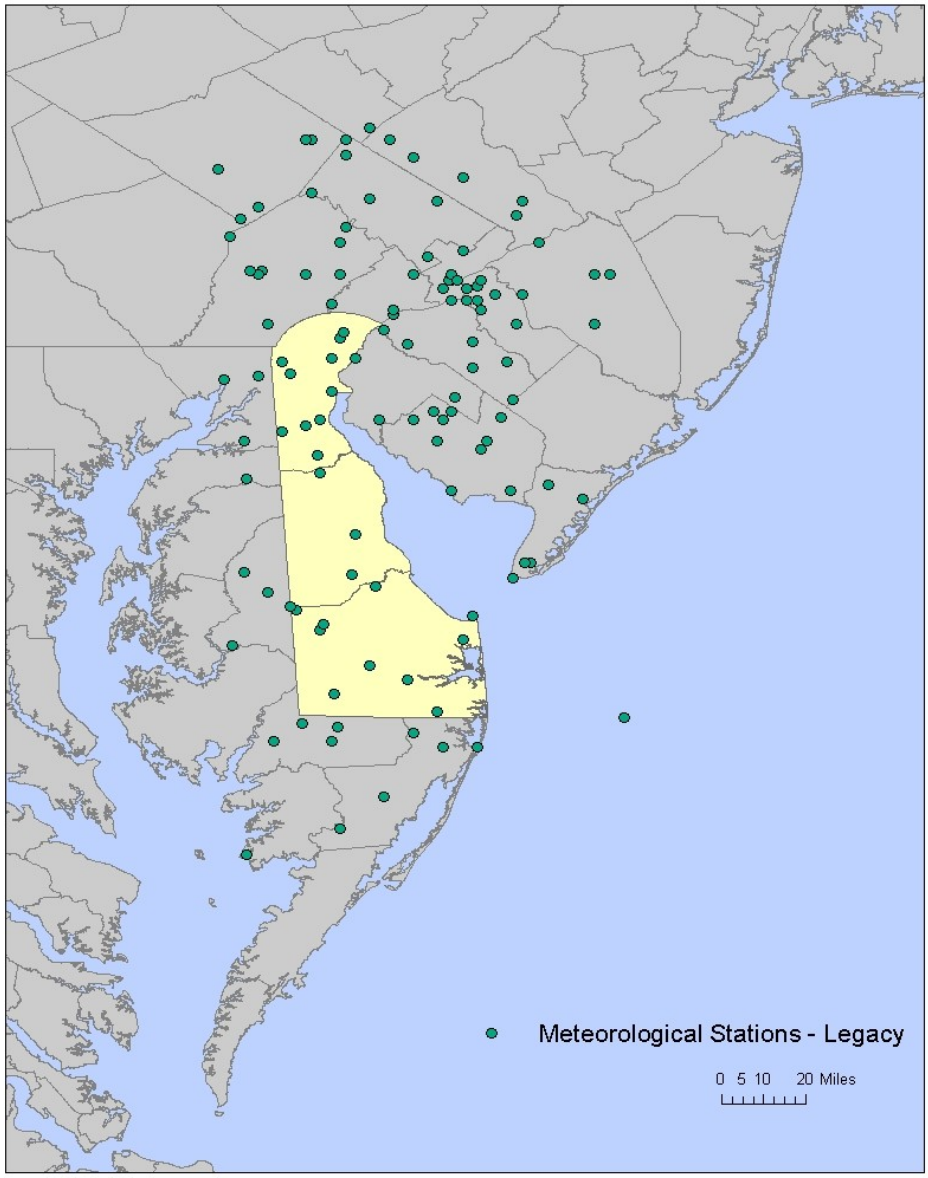

Figure 2.4. Legacy meteorological stations that are no longer making observations across the Delmarva Region.

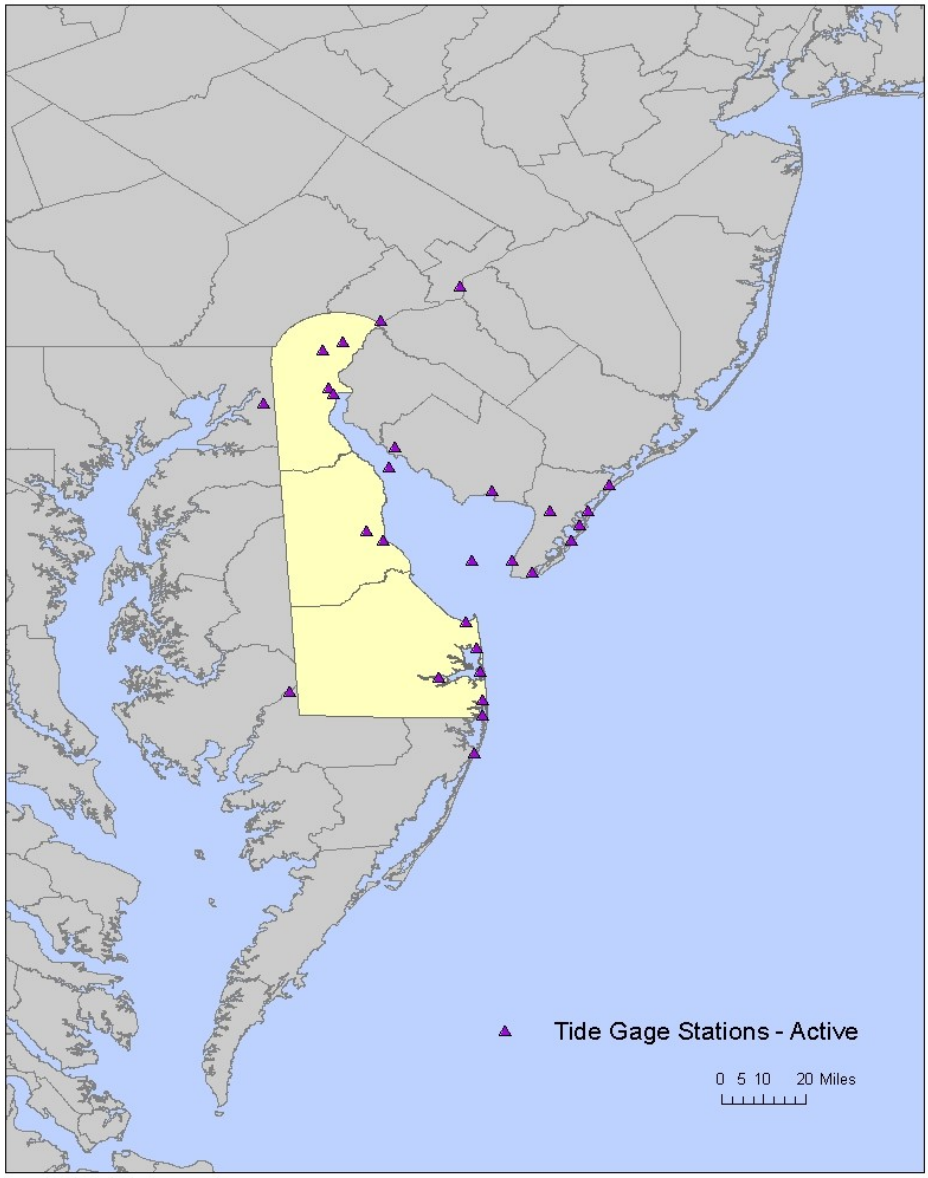

Figure 2.5. Location of stations currently making tidal water level measurements in the Delmarva Region.

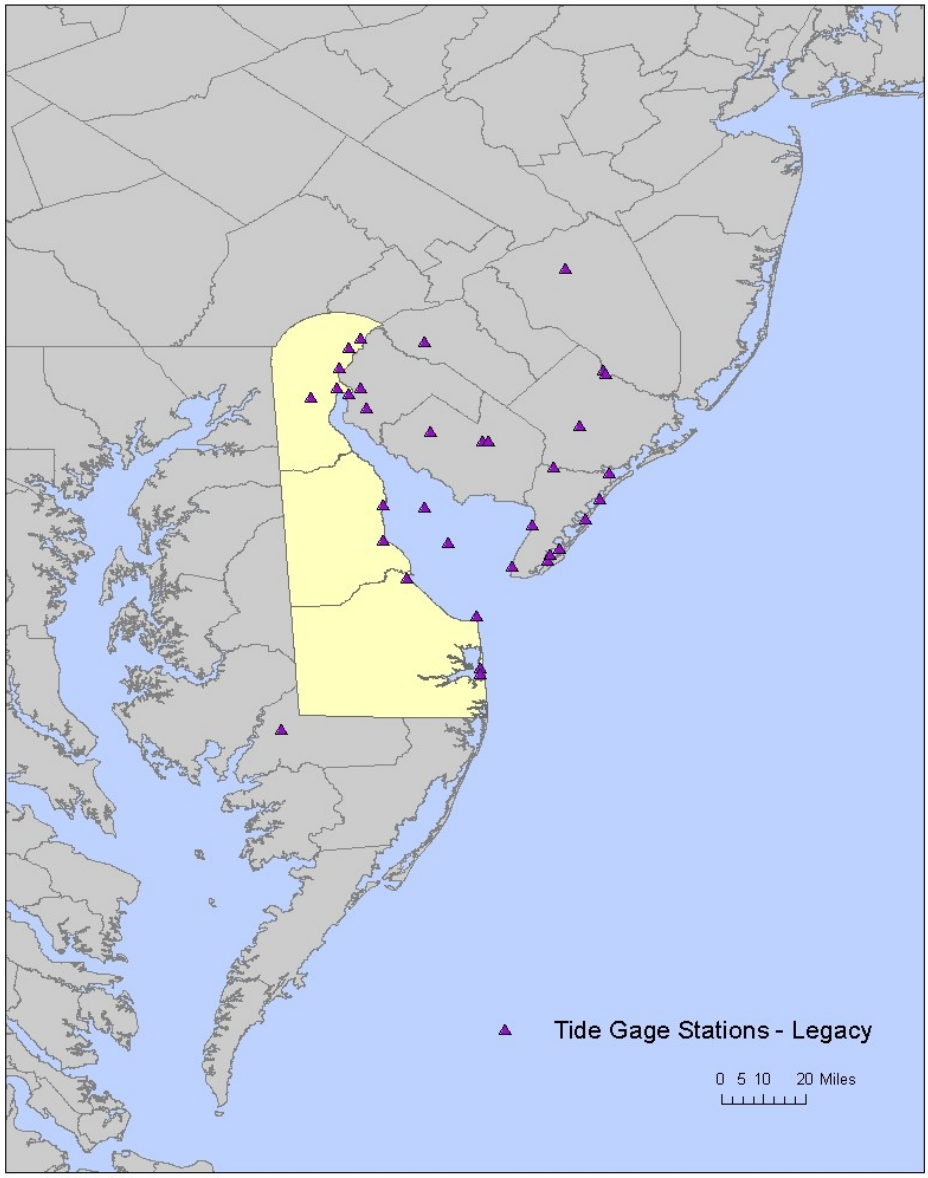

Figure 2.6. Legacy tidal water level stations that are no longer making observations across the Delmarva Region.

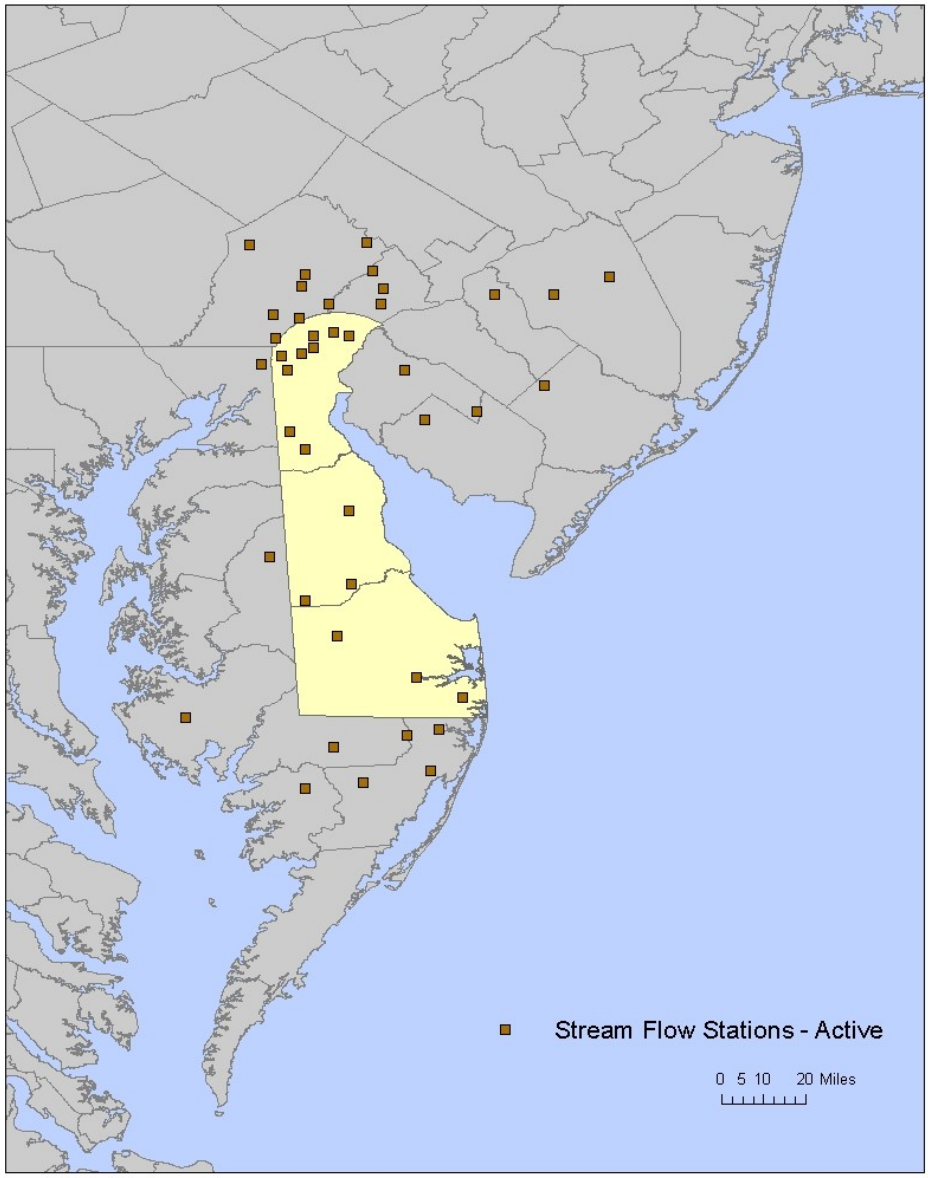

Figure 2.7. Location of stations currently making stream flow measurements in the Delmarva Region.

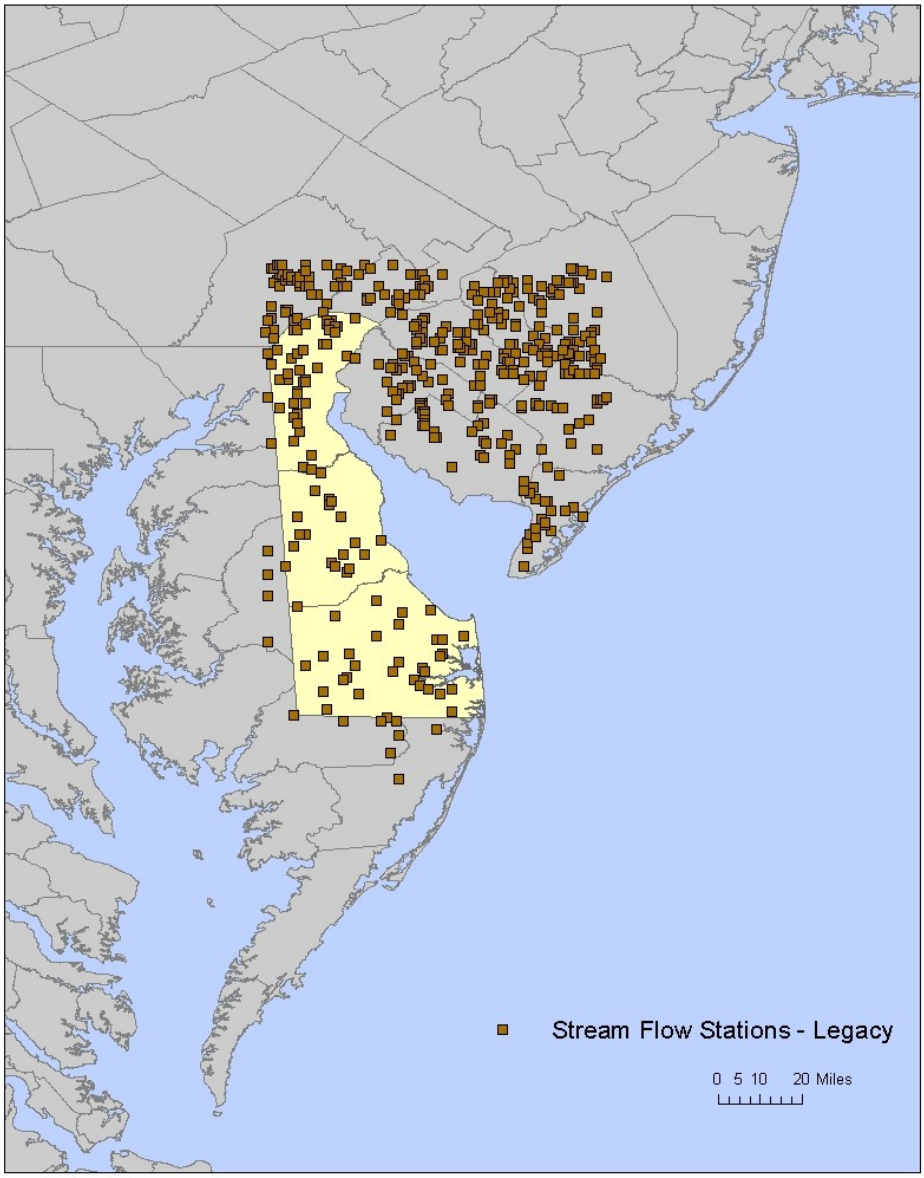

Figure 2.8. Legacy stream flow stations that are no longer making observations across the Delmarva Region.

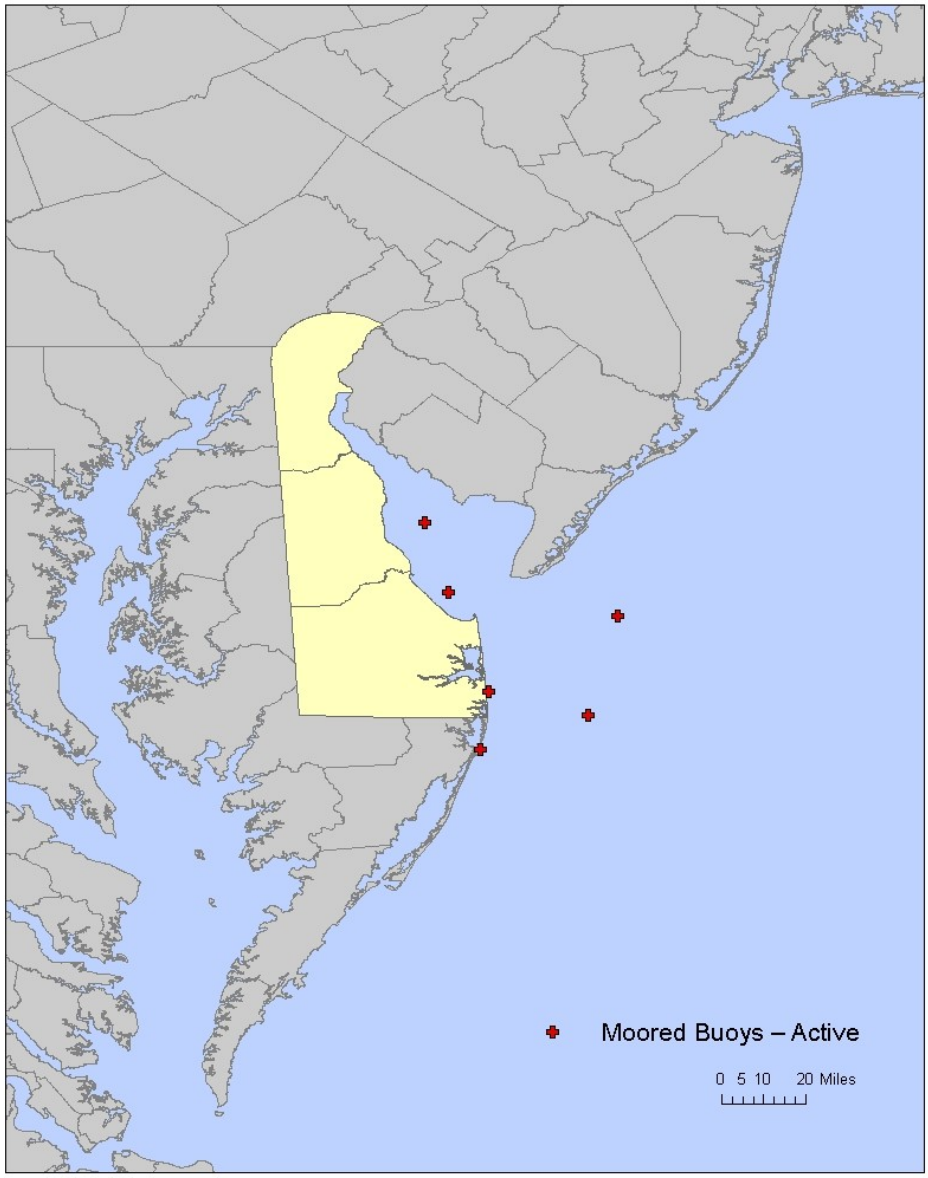

Figure 2.9. Moored buoys currently making observations across near shore coastal waters of Delaware.

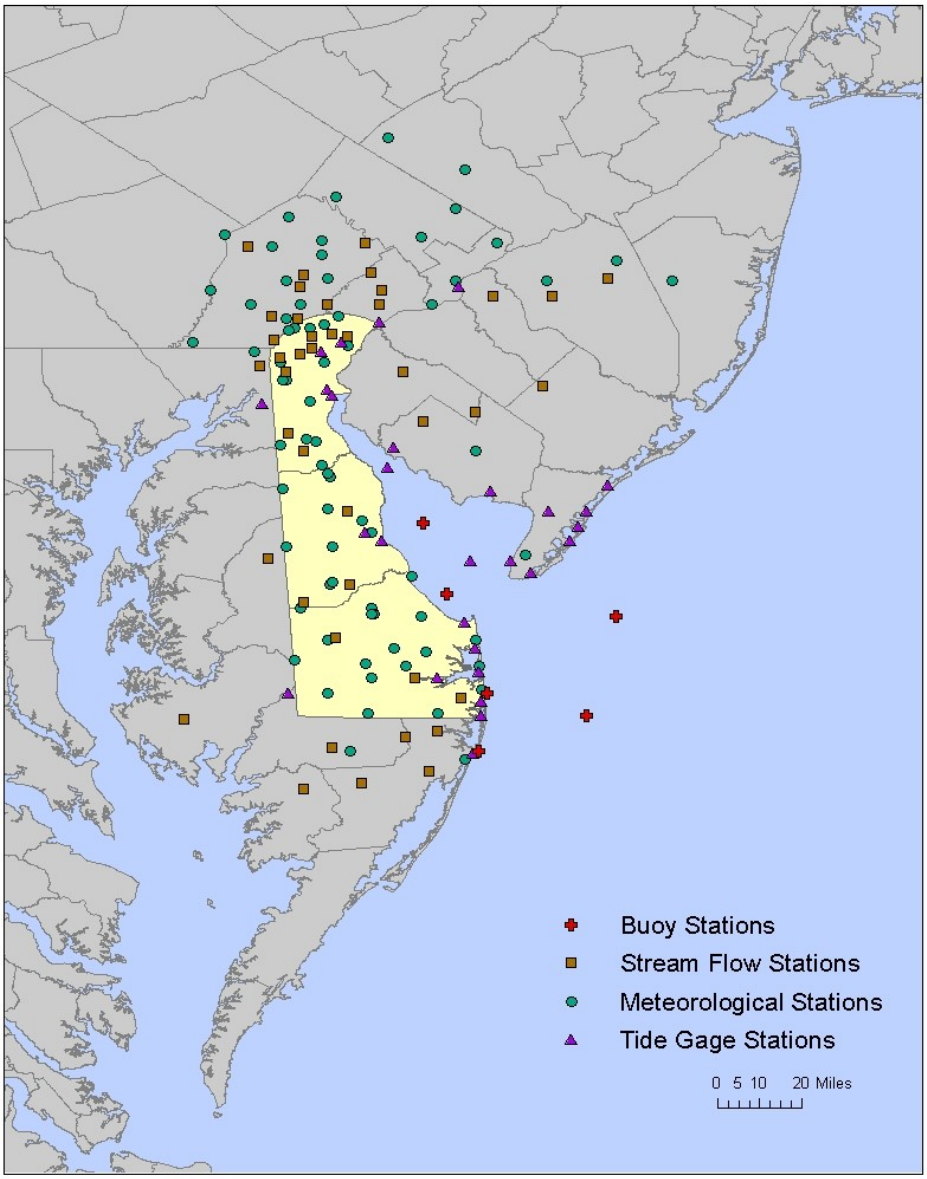

Figure 2.10. Locations of stations that observe and report coastally sensitive data in real-time across the Delmarva Region.

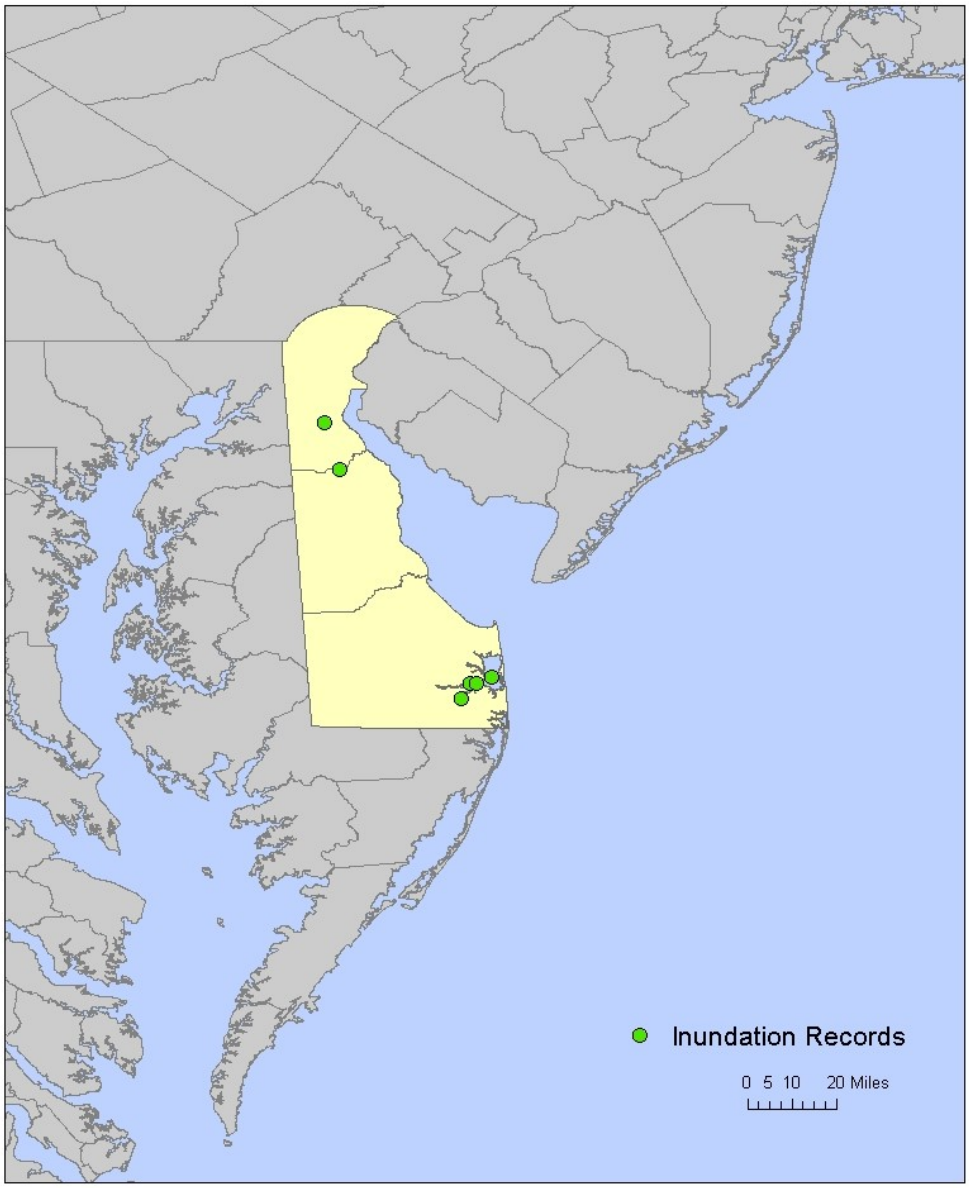

Figure 3.1. Location of non-digital (handwritten) inundation records that have been scanned for use in future coastal flooding research.

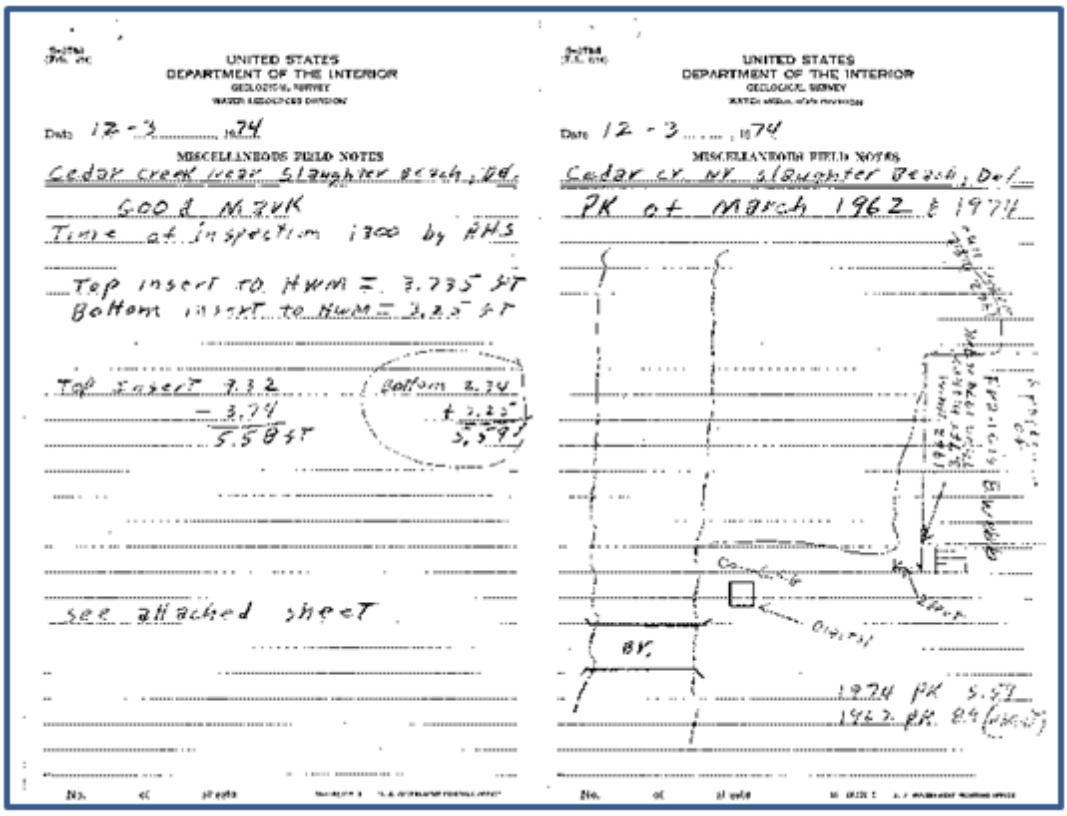

Figure 3.2. Sample of non-digital record of water level. Note complicated calculation of water level which is spatially and temporally non-homogeneous across stations.

Appendices

Appendix 1. Meteorological stations currently making observations across the Delmarva Region.

Appendix 2. Legacy meteorological stations that are no longer making observations across the Delmarva Region.

Appendix 3. Tidal monitoring stations currently making observations across the Delmarva Region.

Appendix 4. Legacy tidal monitoring stations that are no longer making observations across the Delmarva Region.

Appendix 5. Stream flow stations currently making observations across the Delmarva Region.

Appendix 6. Legacy stream flow stations that are no longer making observations across the Delmarva Region.

Appendix 7. Moored buoys currently making observations across near shore coastal waters of Delaware.

Appendix 8. Inland inundation level data recorded during major coastal flooding events. Data are sorted by date of coastal storm.